Global Snow Signature in Ku-Band Backscatter

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Abstract – We present Ku-band backscatter signatures of snow for applications to global snow monitoring with NASA Scatterometer (NSCAT) on the ADEOS satellite and the SeaWinds scatterometer on the QuikSCAT satellite. We carried out the 1999 Alaska Snow Experiment to study the relation between Ku-band backscatter and snow physical properties. The experimental results are applied to interpret backscatter data acquired by the satellite scatterometers. Results from NSCAT show regional patterns matching various global snow types, early snow melt conditions, and the snow event leading to the 1997 Flood of the Century in the U.S. midwest regions and in Manitoba of Canada. SeaWinds/QuikSCAT results reveal the expansion and retreat of global snow cover during the 2000 snow season. The anomalous warming event in late December 1999 was captured by the satellite data.

INTRODUCTION

Snow influences the global heat budget and has strong feedbacks with the planetary albedo and outgoing longwave radiation. Snow cover is a significant climatic index, which can be used to predict and estimate the magnitude of recent changes in climate. Temperature change in high latitudes is attributable to the albedo-temperature feedback process, and snow must be regarded as one of the key variables in the global change monitoring. Different results from various general circulation models indicate that snow feedback involves complex interactive processes in the global climate system.

Snowmelt is an important water source for irrigation and drinking in many areas of the world. Heavy snow storms with rapid snowmelt in spring were accounted for the Flood of the Century in the Northern Plains causing loss of lives and several billion dollars in flood related damages. With this regard, snow monitoring with a frequent coverage over regional scales is necessary for hazard prediction and mitigation. In this paper, we present the application of scatterometry to global snow remote sensing using Ku-band backscatter data.

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PRINCIPLE

Snow grain sizes range mostly in submillimeter and millimeter scales and depth hoar crystals can develop to centimeter scales. For a snow grain much smaller than the electromagnetic wavelength, the scattering follows the Rayleigh scattering law, which dictates that the backscatter is proportional to the fourth power of the wave frequency.

Radar measurements of dry snow [1] show that backscatter agrees well with the Rayleigh-scattering fourth-power slope up to the Ku-band frequency of 14 GHz. An important indication of these results is that snow backscatter at Ku-band 14 GHz is 5.8 times stronger than that at X-band 9.9 GHz, 48 times compared to C-band 5.3 GHz, 2400 times to S-band 2.0 GHz, and 15735 times to L-band 1.25 GHz. With such a strong response to snow, a higher-frequency radar is better to detect thinner snow.

While electromagnetic waves at higher frequencies have a stronger response to snow scattering, wave attenuation needs to be considered. A scattering medium such as snow is inherently dispersive and the wave attenuation is more severe at higher frequencies. Because of the attenuation, backscatter from snow cannot increase further and becomes saturated after a certain snow depth where the waves cannot reach. The saturation effect was shown in experimental data and empirical models at 9.0 GHz and at 16.6 GHz [2].

With the above considerations, a 14-GHz scatterometer system such as NSCAT [6] is well applicable to snow monitoring. A lower frequency radar has a much weaker snow backscatter response that is harder to detect thinner snow, is contaminated by more noise due to a lower signal-to-noise ratio, and is significantly affected by other constituents such as vegetation within the resolution cell. A higher frequency radar is limited by the saturation that causes great difficulties in detecting thicker snow depth and requires a much higher relative accuracy.

NSCAT AND QUIKSCAT DATA

The National Aeronautics and Space Administration (NASA) Scatterometer (NSCAT) was operated at about 14 GHz on the Advanced Earth Observing Satellite (ADEOS) from September 1996 to June 1997. NSCAT had double-sided swaths, each with a coverage of 600 km spanning a range of incidence angles within 10° to 70°. There were 3 beams with the vertical polarization and 1 beam with the horizontal polarization on each side. The relative accuracy of backscatter measurements was estimated to be about ± 0.3 dB and further information on NSCAT has been reported by Tsai et al. [1999]. In this paper, we use the vertical polarization data because there were more data at that polarization and because most snow is isotropic. The NSCAT backscatter resolution was approximately 7 km by 25 km on the ground and the data were binned into 25-km cells.

The QuikSCAT satellite was successfully launched at 7:15 p.m. Pacific Daylight Time on 19 June 1999 from the Vandenberg Air Force Base in California. The satellite carries the SeaWinds scatterometer for ocean wind measurements [4]. The scatterometer has been collecting data at 13.4 GHz on both ocean and land. Backscatter data, at a radiometric resolution tion of 7 km $\times$ 25 km, are acquired with the vertical polarization (σ_{VV}) at a constant incidence angle of 54° over a conical-scanning swath of 1800 km, and with the horizontal polarization (σ_{HH}) at constant 46° over a 1400-km swath. Over cold land regions, the large swath can provide two coverages per day. The satellite orbit was stabilized, the scatterometer performance was verified, and the calibrated science data have been obtained since 19 July 1999 [5].

1999 ALASKA SNOW FIELD EXPERIMENT

To investigate the relationship between Ku-band radar backscatter and physical properties of snow, we carried out a snow field experiment in Ft. Wainright, Alaska, in March and April 1999 [7]. We obtained Ku-band backscatter signatures from a tower-based Ku-band scatterometer, together with detailed snow physical characteristics including snow depth, density, snow water equivalent, grain size distribution, temperature, wetness, and layering.

We made simultaneous suites of measurements of the snow cover albedo in order to link the Ku-band measurements directly to a climatologically important parameter. Measurements were obtained from three distinct phases of the melt: 100% snow cover with diurnal freeze-thaw effects, discontinuous snow cover with extreme freeze-thaw effects, and ground thaw with residual snow (thaw depth from 0 cm to 10 cm). In all cases, backscatter was measured over a large range of incidence angles with multiple polarizations. Several special cases were also investigated by artificially altering the snow and ground cover. The snow field experimental results are applicable to the interpretation of Ku-band backscatter data acquired by NSCAT and QuikSCAT.

RESULTS

Results from the Alaska Snow Experiment show that Ku-band backscatter is sensitive to snow properties. A few percent change of wetness in the surface layer of snow can cause more than 10 dB change in Ku-band backscatter. This leads a strong diurnal variations during the melt and freeze processes, which we exploit to develop an algorithm to determine the timing and spatial pattern of snow melt onset, melt duration, and snow departure. This also indicates that Ku-band backscatter can be used as an early indicator of snow melt conditions. Since Ku-band backscatter is sensitive to snow properties, spatial distributions over different regions of global snow cover can be used to distinguish the extent of different snow types.

Using global NSCAT data, we show for the first time that global Ku-band backscatter signature in snow-covered regions, delineated by the operational NOAA/NESDIS and CPC snow extent product, reveals patterns corresponding to different global snow classes defined by the CRREL snow classification system [8]. Such observations hold over regions with different vegetation types and forest areas during the snow season. This is an indication of the sensitivity of Ku-band backscatter to snow physical characteristics on the global scale.

The comparison of global NSCAT backscatter data with in-situ snow depth and temperature data obtained from the global weather station network over three different and important snow-covered regions of the world, including Alaska in U.S., Ontario in Canada, and Siberia in Russia, shows the close correlation of the NSCAT backscatter retreat patterns with the snow melt process observed at various weather stations. These results further indicate the sensitivity of Ku-band scatterometer in monitoring the global snow cover.

To illustrate the practical utility of wideswath Ku-band scatterometer as an early indicator of large-scale snow melt causing floods, we investigate NSCAT backscatter signature corresponding to snow events leading to the 1997 Flood of the Century over the U.S. northern plains and the Canadian prairie region. NSCAT backscatter shows dramatic changes with pronounced and dynamic patterns correlated with the April blizzard and rapid snow melt causing the devastating flood.

We develop an algorithm for QuikSCAT data to account for the geophysical change before the snow season and use it to determine the backscatter change due to snow accumulation. SeaWinds/QuikSCAT results reveal the expansion and retreat of global snow cover during the 2000 snow season. Circumpolar patterns in the counter-clockwise direction over snow covered regions are observed from QuikSCAT and NSCAT data animations. Distinctive melt bands over snow are identified over north America and across from Europe to east Siberia.

Daily QuikSCAT images reveal an anomalous warming in December in Alaska. On 12/17/99, strong backscatter due to snow cover over almost all of Alaska. However, the image on 12/22/99 exhibits a dramatic reduction in backscatter change over extensive and north-west Canada. On 12/30/99, backscatter change recovered and became even stronger than that on 12/17/99, probably due to additional snow accumulation under cold condition after the warming event. Such a warming event can introduce an ice layer in the snow pack resulting in the instability leading to snow avalanche.

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